CHAPTER 13

Navigation Model Studies

13-1. General. Development of deep-draft navigation projects affected by tides, river currents, and wave effects will in most cases require the use of models and ship simulator studies. Designers and planners should not miss the opportunity for meaningful dredging and cost savings by significant changes in dimensions or layout of navigation channels. Changes in ship type, draft, or size, and modifications to navigation traffic patterns should also be assessed using appropriate models and ship simulator studies. As a part of project feasibility and design, it may be necessary also to provide for some field data gathering of ship maneuvering and wave motion, if warranted. Navigation model studies are used to determine the adequacy of a proposed project improvement plan and to develop possible design modifications to ensure project safety and efficiency and minimize environmental impacts. Figure 13-1 presents a classification diagram of the various study techniques used in navigation project investigations. Physical and numerical models can be used to analyze some of the factors influencing project design and operation.

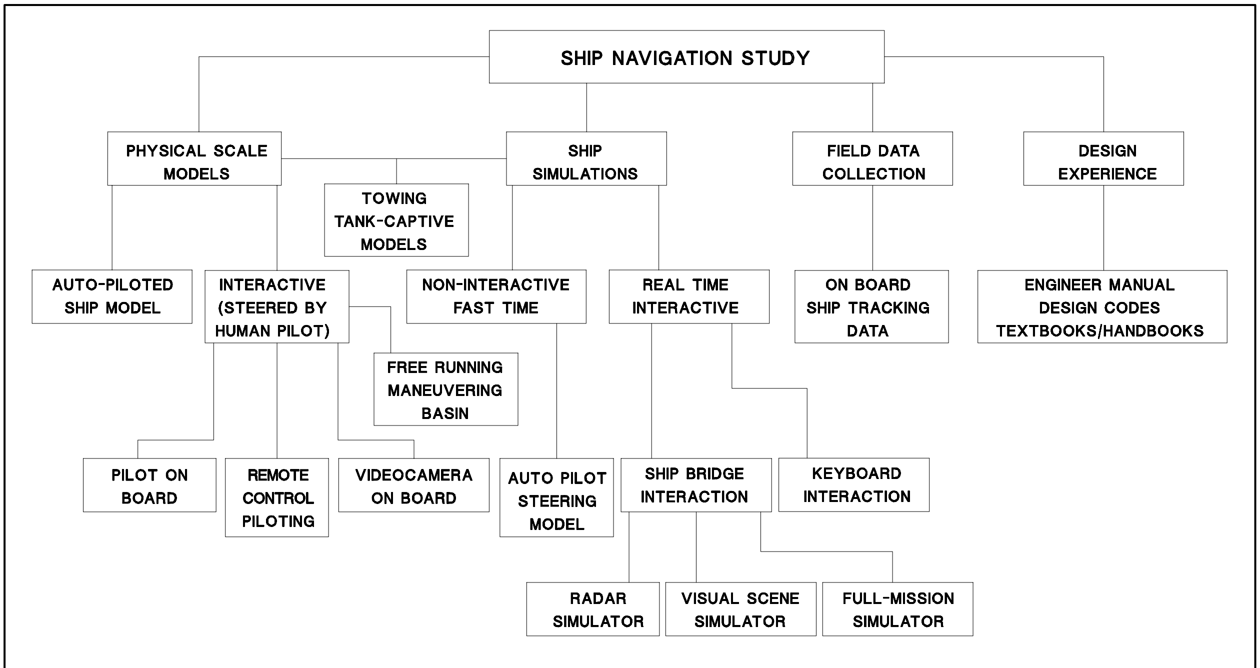


Figure 13-1. Navigation investigation techniques

Because of the complexity of tidal and river currents and effects of wind, waves, sediment movement, etc. on ship navigation, combinations of physical scale models, numerical models, and computer-based ship simulation models are often necessary to resolve proposed project issues. Sediment problems and salinity intrusion in estuarine areas often require extensive field data gathering and modeling efforts to obtain accurate evaluation of the conditions that can be expected with each plan and modification considered. EM 1110-2-1607 gives extensive coverage of needed comprehensive model studies in estuarine areas.

13-2. Physical Models. Physical scale models are used principally to investigate flow patterns where complicated three-dimensional (3-D) effects are important in the study areas of concern. Recent dramatic advances in computer hardware and software have led to a preference to use numerical models to replace and supplement physical model studies. The following types of navigation investigations can be conducted with physical models:

a. Shoaling and erosion characteristics.

b. Salinity intrusion.

c. Wave penetration and harbor response.

d. Jetty design and armor stability.

e. Ship response to waves.

f. Channel width in critical navigation reaches.

g. Tide heights and current patterns.

h. Navigation conditions.

13-3. Numerical Models.

a. *Introduction.*

(1) Numerical modeling is a rapidly developing discipline that can be attributed to the general availability of fast, large-memory computers. A numerical model basically consists of a numerical algorithm developed from the differential equations governing the physical phenomena. All numerical models require the study area to be discretized by a grid or mesh. Furthermore, testing the numerical results against a prototype data set (verification) is highly recommended.

(2) Numerical models may be used to replace or supplement physical models. A study of the following types of investigations with numerical models can:

(a) Provide general circulation patterns for deep- or shallow-draft ship simulator studies.

(b) Determine shoaling and erosion characteristics.

(c) Address dredged material disposal issues and other water quality measures.

(d) Investigate salinity intrusion.

(e) Study wave penetration and harbor response.

(f) Evaluate training structure designs.

(3) Numerous numerical models are available within the scientific community. These models differ in several ways: formulation, governing equations, and user friendliness, to name a few. Some numerical models have the ability to solve hydrodynamics and transport equations simultaneously while others are uncoupled.

(4) The two basic numerical model formulations are finite difference and finite element. Finite difference is the easiest to conceptualize. A finite difference model approximates the calculus differential operators by differences over finite distances. This gives an approximation of the governing equations at discrete points. The finite element model approximates the mathematical form of the solution and inserts it into the exact form of the governing equations. After boundary conditions are imposed, a set of solvable simultaneous equations is created. The finite element solution is continuous over the area of interest.

(5) The governing equations describe the physical processes that are being solved in the model. The dimensionality of the problem is dictated within these equations. These equations describe the physics of the problem. For a hydrodynamic model, these would include items such as friction, density, gravity, rotation of the earth, wind, rain, inflows, and outflows.

(6) The term user friendly is an all-encompassing issue dealing with ease and efficiency of use. It addresses the process of creating a mesh, specifying the parameters within the computational domain, analyzing the solutions, generating presentation and report quality graphics, on-line documentation, and consultation support.

(7) Several models are available within the USACE that have met the test of time. One such model is the TABS-MD numerical modeling system. The multidimensional aspects of TABS-MD have expanded the capabilities of the system such that it has had hundreds of applications within the USACE. TABS-MD has been utilized by a multitude of private consulting firms and universities as well. It has a good reputation and a state-of-the-art graphical user interface that makes it one of the most user-friendly and efficient ways to conduct a numerical model study. Numerous technical reports and papers have been published on TABS-MD applications, the most recent of which are listed in Appendix A.

b. TABS-MD Numerical Modeling System.

(1) The TABS-MD is a collection of several generalized finite element models and pre- and post-processing utility programs integrated into a multidimensional numerical modeling system. TABS-MD is suitable for use in solving hydraulics behavior, sedimentation, and transport problems of rivers, reservoirs, wetlands, estuaries, and bays. Examples of past use include predicting flow patterns and erosion in a river reach constricted by a cofferdam, evaluating sedimentation rates in a deepened navigation channel (both riverine and estuarine), determining the impact of flood control structures on salinity intrusion, developing recommendations for a safe and cost-effective navigation channel design, and defining flow and sedimentation impacts to wetlands.

(2) The system is designed for use by engineers and scientists who are knowledgeable of the physical processes that control behavior of waterways, but who may not be computer experts.

TABS-MD offers a complete range of model study functions, including map digitization, mesh generation, modeling, and graphical display of numerical model results.

(3) TABS-MD is currently operational on a wide variety of computer platforms, ranging from super computers to personal computers (PC). The numerical models and the utility programs are written in FORTRAN-90. Plans are underway to modify the models to take advantage of parallel processor environments.

(4) The system is maintained by the ERDC/WES and includes two hydrodynamic models: RMA2-WES and RMA10-WES. In this context, the term hydrodynamic modeling is a general term intended to denote a body of water with a free surface such as a river. The first fundamental decision, prior to conducting a numerical model study, is to classify the study area in order to choose the appropriate numerical model. RMA2-WES is an appropriate choice for a far-field problem whose study area may be modeled with a two-dimensional (2-D) depth-averaged approximation. Otherwise, the modeling effort must employ RMA10-WES to incorporate the 3-D aspects. TABS-MD permits an efficient numerical approach by incorporating multiple dimension concepts within a given mesh domain. For instance, an RMA2-WES application may use economical one-dimensional (1-D) calculations in some areas and 2-D calculations within the primary area of interest. An RMA10-WES application may use any combination of 1-, 2-, and 3-D calculations with or without the transport options. The modeling effort can reach a high degree of complexity and computational burden with 3-D computations.

(5) Two sediment transport options are available with the TABS-MD system. SED2D is a 2-D finite element model that solves the convection-diffusion equation with bed source-sink terms. These terms are structured for sand or cohesive sediments. Cohesive deposited material forms layers, and bookkeeping allows layers of separate material types, deposit thickness, and age. SED2D uses the hydrodynamic solution generated by the RMA2-WES model. RMA2-WES and SED2D are uncoupled; therefore, a new geometry must be cycled back to RMA2-WES when the bed deposition and erosion patterns begin to significantly affect hydrodynamics. Work is ongoing to upgrade SED2D to accommodate all features of RMA2-WES, such as 1-D and marsh/wetland calculations. The other sediment transport option is to couple the sediment transport with the hydrodynamic calculation by using RMA10-WES. RMA10-WES includes a single-class fine-sediment transport with an associated layered bed with distinct densities and erodibilities for each layer. Changes in bed elevation are made during computations and are accounted for in the continuity equation.

(6) There are two water quality transport options within TABS-MD as well. RMA4-WES is a 1-D and 2-D finite element model with a form of the convective diffusion equation with general source-sink terms. The model may transport and route up to six constituent substances, with or without decay. The model accommodates a mixing zone outside the model boundaries for estimation of reentrainment. RMA4-WES uses the hydrodynamic solution generated by the RMA2-WES model. RMA10-WES has the option to couple temperature, salinity, and/or sediment transport with the hydrodynamic calculations.

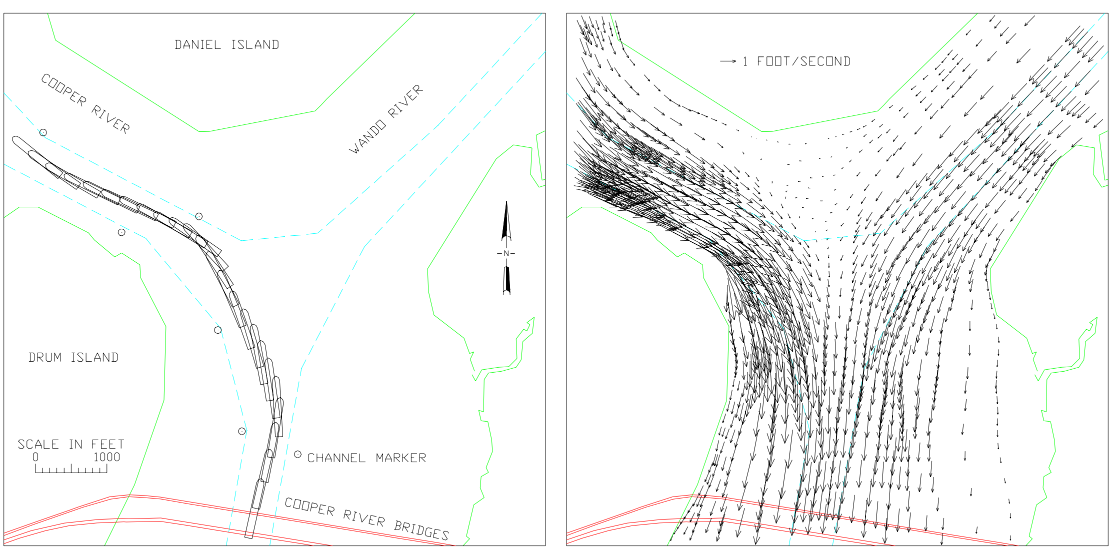
(7) A recent research effort was conducted at ERDC/WES to provide guidelines and help field offices conduct hydrodynamic numerical models to address both deep-draft and shallow-draft issues. The work emphasized RMA2-WES hydrodynamic applications since all

navigation studies involve that aspect and most of the field offices have access to personal computers or workstations capable of running 2-D simulations. Furthermore, the ERDC/WES ship simulator typically uses the RMA2-WES solution as input to define the currents for the simulator (Figure 13-2).

c. *Example Navigation Applications Using RMA2-WES Solutions.*

(1) *Charleston, SC, Estuary*. The study was undertaken to evaluate and optimize proposed improvements including deepening the navigation channel from 12 to 14 m (40-45 ft), realigning and/or widening several fairways along a 8-kilometer (5-mile) stretch of the estuary, and locating a proposed seven-berth container terminal. The RMA2-WES simulation was conducted to provide currents to the ERDC/WES ship simulator for several time-steps on both the ebb and flood portions of a spring tidal cycle. Figure 13-2 shows the ERDC/WES ship simulator response track plot corresponding with one set of velocity vectors computed by RMA2-WES for the Drum Island reach of the study area. The study was an iterative process between the RMA2-WES hydrodynamic model, the ship simulator model, and the SED2D sediment transport model, as indicated by the flowchart in Figure 13-3.

(2) *Redeye Crossing near Baton Rouge, LA, along the Lower Mississippi River*. The study was undertaken to evaluate the effect of river training structures on vessels (both ships and tows) transiting the Redeye Crossing Reach. Studies included a TABS-MD RMA2-WES hydrodynamic model, the ship/tow simulator model, and a SED2D sediment transport model. Figure 13-4a and b show the ERDC/WES tow simulator response track plot corresponding to one set of velocity vectors computed by RMA2-WES using the secondary flow corrector. Figure 13-4c shows the computational mesh used by the TABS-MD models. The study was an iterative process between the RMA2-WES hydrodynamic model, the s hip simulator model, and the SED2D sediment transport model, as indicated by the flowchart in Figure 13-3.



a. WES ship simulator track plot b. RMA2-WES hydrodynamic solution

Figure 13-2. The Cooper River, Charleston, SC channel realignment study

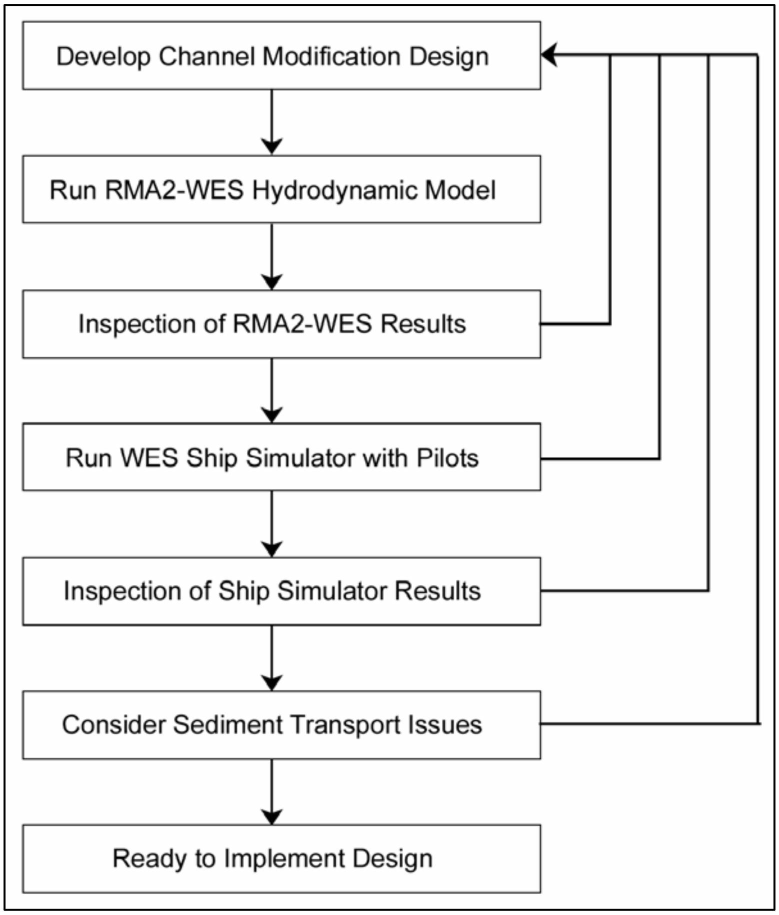
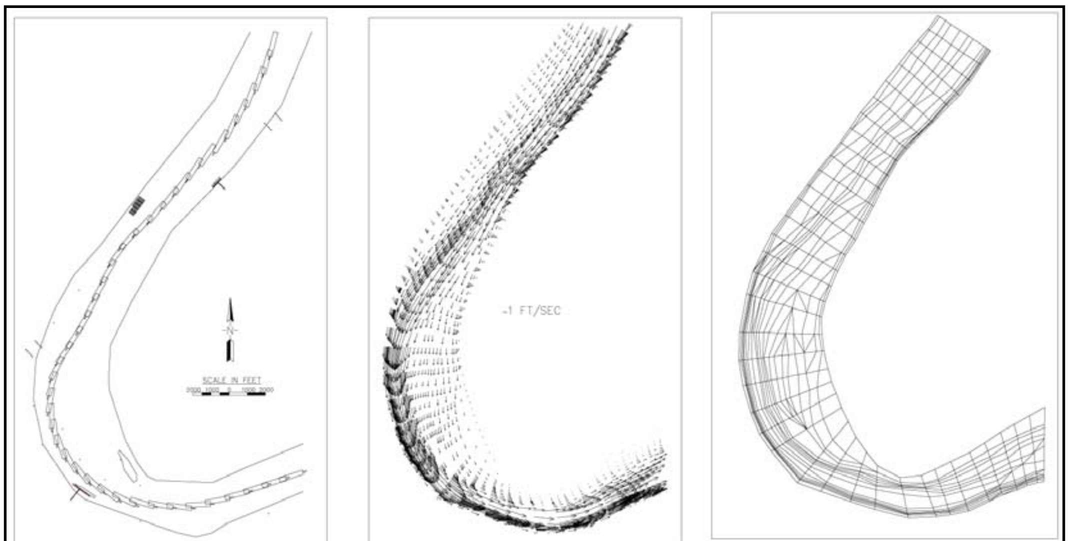


Figure 13-3. Typical events and feedback loops involved in ERDC/WES ship simulator study



a. ERDC/WES tow simulator track plots

b. RMA2-WES hydrodynamic solution

c. Numerical model computational mesh

Figure 13-4. Redeye Crossing of the Lower Mississippi River *d. RMA2-WES Hydrodynamic Model.* RMA2-WES is a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with Manning's equation, and eddy viscosity coefficients are used to define the turbulent exchanges.[1] A velocity form of the basic equation is used with side boundaries treated as either slip or static. The model has a marsh porosity option as well as the ability to automatically perform wetting and drying. Boundary conditions may be water-surface elevations, velocities, discharges, or tidal radiation. Both steady and unsteady free-surface calculations for subcritical flow problems can be analyzed.

(1) *RMA2-WES governing equations*.

(a) The generalized computer program RMA2-WES solves the depth-integrated equations of fluid mass and momentum conservation in two horizontal directions. The forms of the solved equations are:

$$\begin{aligned}
&h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+hv\frac{\partial u}{\partial y}\\
&-\frac{h}{\rho}\left(E_{xx}\frac{\partial^2 u}{\partial x^2}+E_{xy}\frac{\partial^2 u}{\partial y^2}\right)\\
&+gh\left(\frac{\partial a}{\partial x}+\frac{\partial h}{\partial x}\right)\\
&+\frac{gun^2}{\left(1.486h^{1/6}\right)^2}\left(u^2+v^2\right)^{1/2}\\
&-\varsigma\ V_a^2\cos\Psi-2h\omega v\sin\Phi=0
\end{aligned}\tag{13-1}$$

$$\begin{aligned}
&h\frac{\partial v}{\partial t}+hu\frac{\partial v}{\partial x}+hv\frac{\partial v}{\partial y}\\
&-\frac{h}{\rho}\left(E_{yx}\frac{\partial^2 v}{\partial x^2}+E_{yy}\frac{\partial^2 v}{\partial y^2}\right)\\
&+gh\left(\frac{\partial a}{\partial y}+\frac{\partial h}{\partial y}\right)\\
&+\frac{gvn^2}{\left(1.486h^{1/6}\right)^2}\left(u^2+v^2\right)^{1/2}\\
&-\varsigma\ V_a^2\sin\Psi+2\omega hu\sin\Phi=0
\end{aligned}\tag{13-2}$$

[1] Recent improvements to the hydrodynamic model allow the user to employ automatic parameter assignments for roughness and turbulent coefficients as the velocity field changes during a time varying simulation.

$$\frac{\partial h}{\partial t}+h\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}=0 \tag{13-3}$$

where

h = depth (meters (feet))

u,v = velocities in the Cartesian directions (meters/second or feet/second)

x,y,t = Cartesian coordinates and time (meters/second or feet/second)

ρ = mass density of fluid (mass/unit volume) (kilograms/meter^3 or slugs/feet^3)

E = Eddy viscosity coefficient,
for xx = normal direction on x axis surface,
for yy = normal direction on y axis surface,
for xy and yx = shear direction on each surface

g = acceleration because of gravity (meters/second^2 (feet/sec^2))

a = elevation of bottom (meters or feet)

n = Manning's roughness n-value $\left(\frac{\text{sec}}{\text{m}^{1/3}} \text{ or } \frac{\text{sec}}{\text{ft}^{1/3}}\right)$

1.486 = conversion from SI (metric) to non-SI units

ζ = empirical wind shear coefficient

V_a = wind speed (meters/second or feet/second)[2]

ψ = wind direction (radians)[1]

ω = rate of earth's angular rotation (1/sec) [1]

φ = local latitude, Coriolis (radians) [1]

Equations 13-1, 13-2, and 13-3 are solved by the finite element method using the Galerkin Method of weighted residuals. The elements may be 1-D lines, or 2-D quadrilaterals or triangles, and may have curved (parabolic) sides. The shape functions are quadratic for velocity and linear for depth.

(b) Integration in space is performed by Gaussian integration. Derivatives in time are replaced by a nonlinear finite difference approximation. Variables are assumed to vary over each time interval in the form.

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[2] At this point in the equation, there are the units for consistency. User input units may vary.

$$f(t) = f(0) + at + bt^c \quad t_0 \le t \le t_0 + \Delta t \tag{13-4}$$

This is differentiated with respect to time and cast in finite difference form. Letters *a, b,* and *c* are constants. Experiment has shown that the best value for *c* is 1.5 (Norton and King 1977).

(c) The solution is fully implicit and the set of simultaneous equations is solved by Newton-Raphson non-linear iteration. The computer code executes the solution by means of a front-type solver, which assembles a portion of the matrix and solves it before assembling the next portion of the matrix.

(d) RMA2-WES is based on the earlier versions (Norton and King 1977) but differs in several ways. It is formulated in terms of velocity (v) instead of unit discharge (vh), which improves some aspects of the code's behavior. Other differences from the earlier versions include the following:

- Employs new numerical solution algorithms.
- Permits wetting and drying of areas within the mesh.
- Permits wetlands to be simulated as either totally wet/dry or as gradually changing wet/dry states.
- Permits specification of turbulent coefficients in directions other than along the x- and z-axes.
- Accommodates the specifications of hydraulic control structures in the network.
- Permits the use of automatic assignment of friction and turbulent coefficients.
- Permits input in either non-SI or SI units.

(e) Additionally, a numerical corrector for secondary ("bendway") flow has been incorporated into the RMA2-WES model as a result of deep- and shallow-draft research and applications.

- Incorporated a secondary flow ("bendway") corrector.
- Improved the RMA2-WES documentation and provided resolution guidelines.
- Provided an on-line point-and-click documentation capability on the PC.
- Incorporated a documentation icon within the graphical user interface on the PC.

(2) The principle of bendway correction.

(a) The secondary flow (or "bendway") corrector was added to the RMA2-WES model. The modified program, designated as version 4.35, solves a transport equation for streamwise vorticity and converts it to accelerations due to secondary currents. These additional accelerations result in improved predictions of the traditional depth-averaged velocity calculations. Their effect is to reduce velocities on the inside of river bends and increase them on the outside of bends. The modeler may activate or deactivate the secondary flow corrector as required for its application. This enhancement permits RMA2-WES to be successfully used for some study areas that otherwise would have required the 3-D model.

(b) The theoretical basis of bendway correction was developed for the depth-averaged finite difference numerical model, STREMR (Bernard and Schneider 1992).

(c) The bendway correction is accomplished by first solving an additional equation for the transport of streamwise vorticity. Vorticity is a measure of rotation of flow. Streamwise vorticity at a point is equal to the velocity of the fluid about the axis in the streamwise direction of flow. Streamwise vorticity is in the vertical plane perpendicular to the direction of flow and is related to the radial accelerations that cause the helical flow pattern.

(d) The transport equation for streamwise vorticity is

$$\frac{\partial\Omega}{\partial t}+u\frac{\partial\Omega}{\partial x}+v\frac{\partial\Omega}{\partial y}=\frac{A_s\sqrt{C_f}\,|\vec{u}|^2}{Rh\left(1+9h^2/R^2\right)} -D_s\sqrt{C_f}\,\Omega\frac{|\vec{u}|}{h}+\frac{1}{h}\nabla\left(vh\nabla\Omega\right) \tag{13-5}$$

where

Ω = streamwise vorticity

A_s = 5.0

C = friction coefficient

h = water depth

$|\vec{u}|$ = magnitude of the velocity vector

R = local radius of curvature

D_s = 0.5

Units of vorticity are sec^{-1}.

(e) The additional shear stress caused by the secondary, helical flow is calculated from streamwise vorticity at each node. The components of this shear stress are added to the other terms (friction, slope, Coriolis) in the governing equations.

e. RMA2-WES Documentation. With the technological advancements of the computer industry and the evolution of computational algorithms, it was evident that published documentation could be quickly outdated. To address the evolution of the "art" of numerical

modeling, a living approach to documentation was selected. The RMA2-WES "*DOC-TO-HELP*" hypertext documentation is regularly updated and available for download from the World Wide Web (WWW). After downloading it to your PC, you may view the on-line documentation on any PC running windows. The WWW address for the documentation:
http://chl.wes.army.mil/software/tabs/docs.htp

f. *Graphical User Interface.* All USACE and ERDC/WES employees performing surface water analyses for the USACE may obtain a copy of SMS, the Surface Water Modeling System graphical user interface, developed by Brigham Young University (BYU). This graphical user interface was first made available in 1989 and has evolved to its present release. SMS is fully compatible with the TABS-MD suite of models and with many other surface water models. To obtain a copy of the SMS interface, download the proper executable for your computer and complete the request form available from the WWW at this address:
http://chl.wes.army.mil/software/sms

13-4. Ship Simulations.

a. Increasingly, navigation studies of deep-draft channels are being tested for design with ship simulators. A block diagram of the ERDC/WES ship simulator is presented in Figure 13-5. Shiphandling simulators have the distinct advantage over scale models in allowing for testing using human piloting in real-time rather than reduced Froudian time scaling. The inclusion of the local professional pilot in the channel project design process has proved distinctly advantageous in developing a safe and optimum channel. Simulators may be viewed as a special case of numerical models, using one or more dedicated computers and appropriate display equipment and providing real-time interactive input and output during testing. As depicted schematically in Figure 13-6, an appropriate ship simulator includes models of a ship, the navigation channel, the currents, the wind, the visual scene, the radar image, tugs and thrusters, the ship bridge controls, and typical bridge instruments. The simulator can be used with human piloted control in real-time or an autopilot, which follows a track-keeping function for fast-time tests. The ship model must be complete and realistic with appropriate ship hull dynamics; engine thrust; control surface hydrodynamics; cross-term interactions; bank, shallow water, currents, wind, and wave effects; and tug, bow, and stern-thruster forces.

b. The visual and radar models depict the changing scene in enough detail to enable the pilot to determine his location and the rate of motion. The pilot has full access to visual cues and instrumentation information and controls normally available to him as is available onboard the real ship. The visual scene and radar scene include the details of the navigation aids and realistic cultural features often used to pilot ships. The channel model produces the effects on the ship that will cause the ship to respond to the channel similar to the way it does in real life using detailed description of the currents, channel banks, and underkeel clearance throughout the channel test scenarios. For passing situations, accurate modeling of ship force and moment interaction effects must be reproduced. The environmental factors such as wind, currents, and waves cause perturbations on the ship, which are crucial to realistic channel design studies.

c. A block diagram showing the method of operation in real-time simulation is given in Figure 13-7. A more complete description of the ERDC/WES ship simulator and details of study techniques with several project channel design applications are presented in Appendix C.

13-5. Field Data Collection. In some situations, navigation problems can be most expeditiously investigated using onboard instrumentation to measure ship data. An example of this was the extensive 2-year effort to collect ship motion data at the Mouth of the Columbia River to develop data for channel design in very high-wave environment (Wang et al. 1980). The introduction of satellite-based DGPS provides the accuracy required to give ship position data accurate enough to give useful ship navigation channel design guidance. In conjunction with the Houston Ship Channel simulator study, DGPS field data on ship meeting and passing in the 400-ft-wide channel were collected that proved very valuable in channel design.

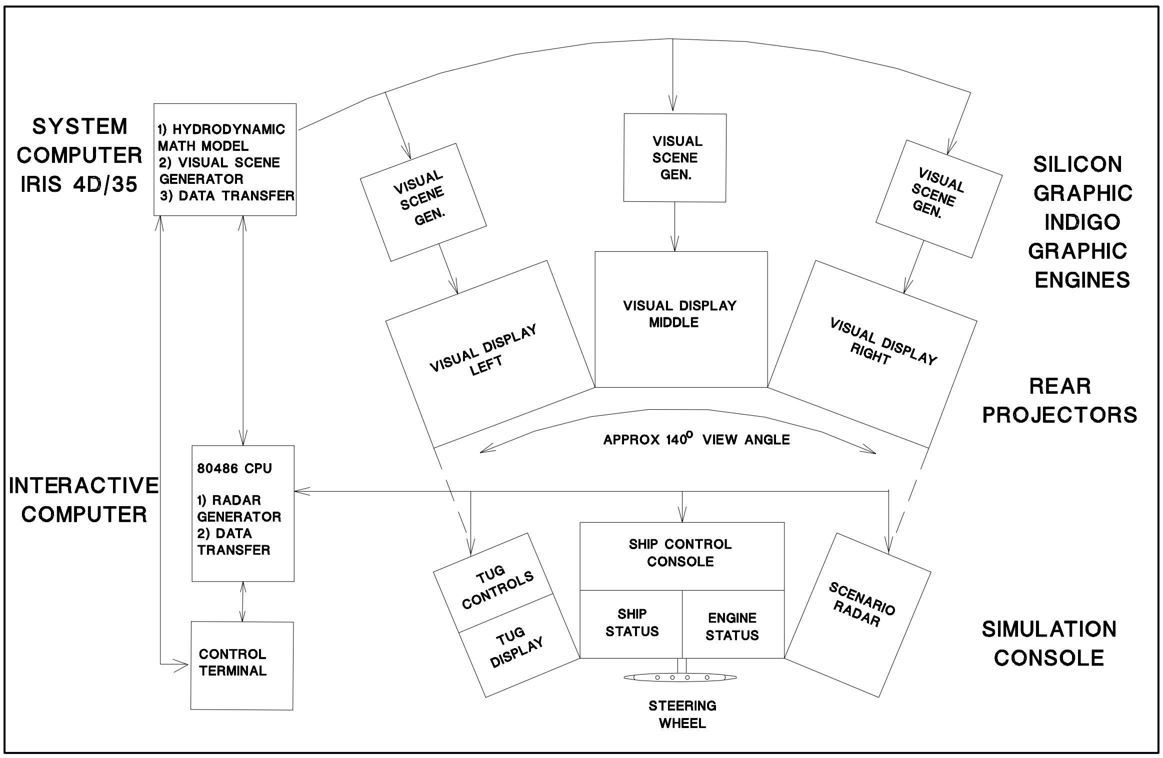

Figure 13-5. WES ship simulator system

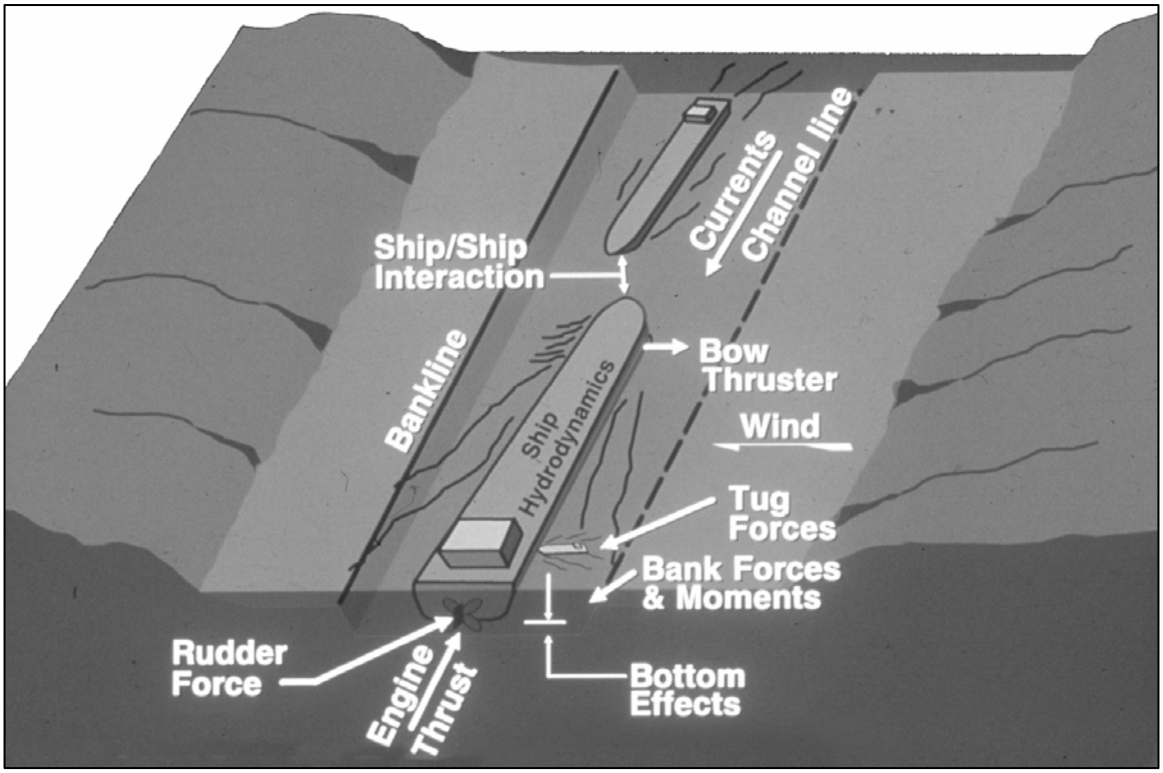

Figure 13-6. Ship simulator forces and effects

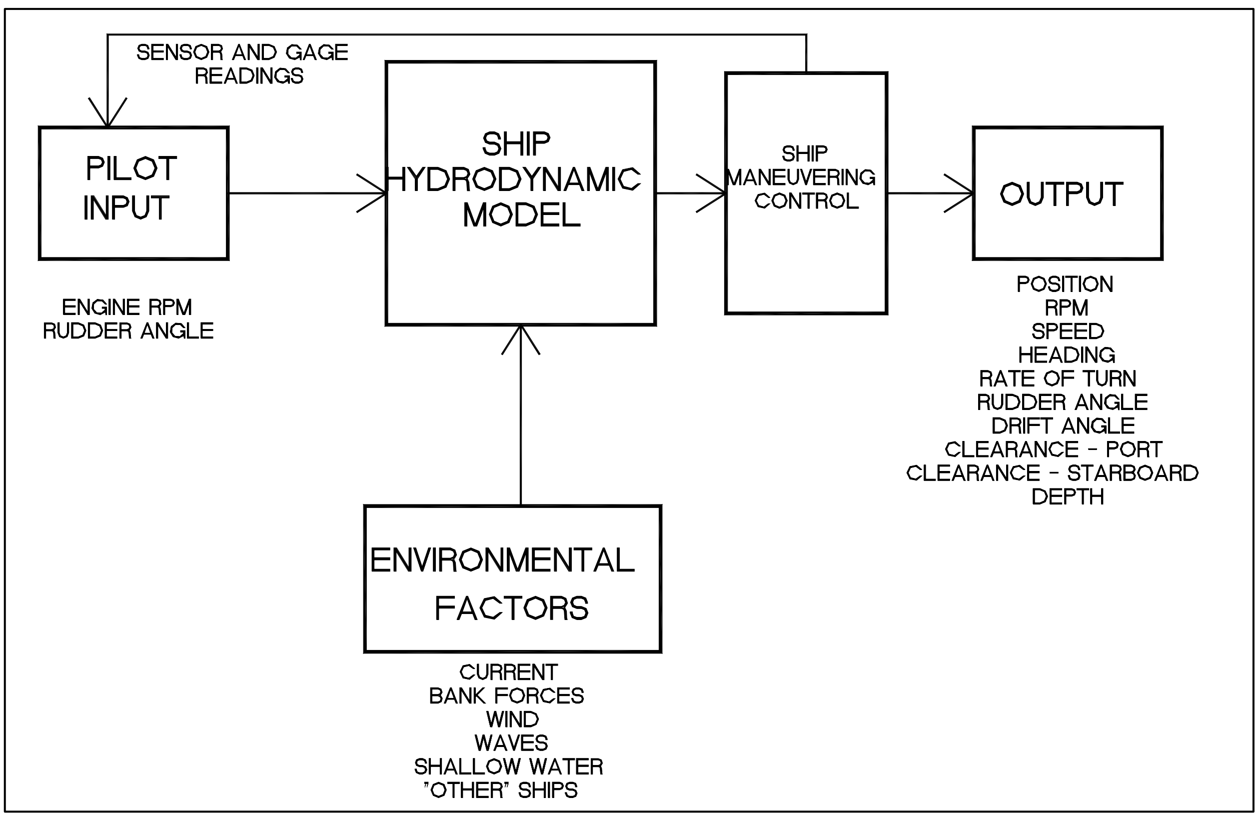

Figure 13-7. Real-time simulation